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Pacific Region
Canadian Science Advisory Secretariat
Science Advisory Report 2015/015

ASSESSMENT OF PACIFIC COD (*GADUS MACROCEPHALUS*) FOR HECATE STRAIT (AREA 5CD) IN 2013

Pacific Cod (Gadus macrocephalus). Credit: Fisheries and Oceans Canada (DFO).

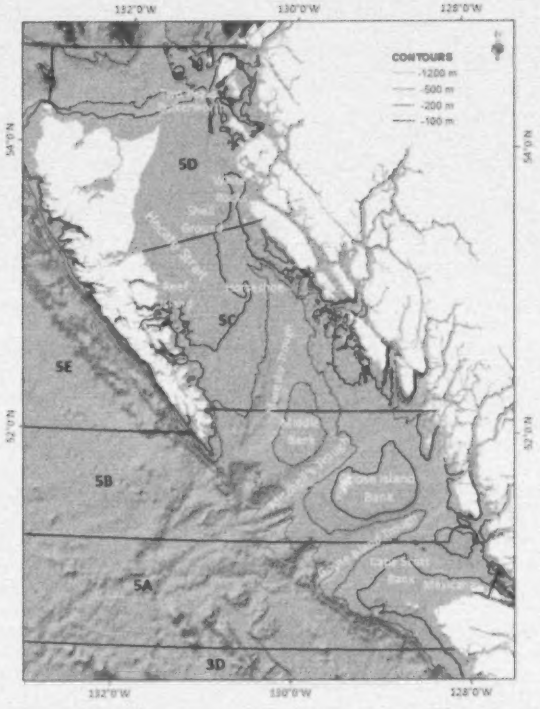

Figure 1. Pacific Marine Fisheries Commission major management areas north of Vancouver Island (indicated by straight black lines). Key Pacific Cod fishing locations are indicated in white text. This assessment refers to Areas 5C and 5D only.

Context

Pacific Cod (Gadus macrocephalus) is a commercially important species of cod that occurs along the entire coast of British Columbia. It is primarily caught by the groundfish trawl fishery and occasionally by the hook and line fishery, with most catch being taken from Hecate Strait (Area 5CD). The Hecate Strait stock has not been assessed since 2004.

Advice was requested by Fisheries Management (FM) on the current stock status and potential yields for Pacific Cod in the waters of British Columbia. A Bayesian delay-difference model was applied to data from Area 5CD, where the majority of the catch occurs.

This Science Advisory Report is from the January 9-10, 2014 Assessment of British Columbia Pacific Cod for Hecate Strait (Area 5CD) and Queen Charlotte Sound (Area 5AB) in 2013. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

April 2015

Canada

SUMMARY

- Pacific Cod (*Gadus macrocephalus*) is a commercially important species of cod that occurs along the entire coast of British Columbia. It is primarily caught by the groundfish trawl fishery and occasionally by the hook and line fishery. The majority of catches are taken in Hecate Strait (Area 5CD, ~700 t in 2013) and Queen Charlotte Sound (Area 5AB, ~180 t in 2013), although large catches were taken historically off the West Coast of Vancouver Island (Area 3CD).
- This advisory report refers only to the Hecate Strait stock, which was last assessed in 2004.
- Pacific Cod stocks in British Columbia are difficult to assess, primarily due to the relatively short time series of fishery-independent index of abundance data, changes in fishery selectivity over time, and historical changes in management and fishery operations. Historical changes include the transition to quotas (from the early 1990s to 1997), the introduction of 100% at-sea observer coverage (February 1996), and several voluntary and regulation mesh-size changes. There is very little reliable age composition data for this difficult-to-age species.
- The status of the Pacific Cod population in Hecate Strait was assessed using a Bayesian delay-difference model fit to fishery–independent survey data, commercial catch-per-unit-effort data, commercial catch data, and estimates of annual mean weights from the trawl fishery.
- Despite large uncertainty, biomass in Hecate Strait is estimated to have been gradually increasing since 2001.
- Recruitment is estimated to have been below the estimated long-term (56-year) average in most years for the past two decades.
- Estimates of fishery reference points based on maximum sustainable yield (MSY) were very sensitive to model assumptions, and differed substantially among model sensitivity cases. Unfished biomass (B_0) was also sensitive to model assumptions. The use of MSY-based and B_0-based reference points was consequently not supported for this stock.
- Alternative "historical" reference points are used based on those accepted for the previous assessment of this stock. They are:
    i. an Upper Stock Reference point based on the estimated average biomass for the period 1956 to 2004;
    ii. a Limit Reference Point defined as the estimated minimum biomass from which the stock recovered to an above-average biomass level (namely the estimated biomass in 1971); and
    iii. a Limit Removal Rate calculated as the estimated average fishing mortality for the period 1956-2004.
- Advice to managers is provided in a decision table that summarizes the probability of breaching reference points at a range of fixed catches for a one-year projection. Due to model sensitivity to a number of model assumptions, the table uses a model-averaging approach intended to integrate results from the use of alternative model assumptions.
- Under a 2014 catch similar to the 2013 catch (approximately 700 t), the projected biomass at the start of 2015 is estimated to have a 0.56 probability of being below the historical Upper Stock Reference point and a 0.17 probability of being below the historical Limit Reference

Point. The probability that the fishing mortality rate in 2014 will be above the Limit Removal Rate is estimated to be zero.

INTRODUCTION

Biology and Stock Structure

Pacific Cod (*Gadus macrocephalus*) is a relatively short-lived, fast-growing member of the family Gadidae. Other common names in British Columbia (BC) include Grey Cod and Gray Cod. Populations of Pacific Cod are distributed from California, through waters off BC, the Gulf of Alaska and the Bering Sea to Russia, Korea, Japan and China. Maximum observed age in British Columbia is thought to be around 10-11 years. The maximum length recorded in British Columbia is 100 cm. Pacific Cod are demersal spawners, with spawning most likely occurring from February to March. Estimated population dynamics of Pacific Cod in BC have been characterized by large apparent variations in abundance since the 1950s.

Four stocks of Pacific Cod are defined for management purposes on the BC coast: Strait of Georgia (4B); West Coast Vancouver Island (3CD); Queen Charlotte Sound (5AB); and Hecate Strait (5CD), although it is unclear whether these are biologically distinct populations. Recent genetic analyses have identified a distinction between North American and Asian Pacific Cod populations, and have shown some evidence for distinction between Alaskan populations and those south of Dixon Entrance in British Columbia. There is also some evidence that fish taken off the coast of Washington and the West Coast of Vancouver Island may be distinct from fish sampled within the Strait of Georgia or Puget Sound. However, genetic linkages between stocks in BC and those in Alaska remain poorly understood.

Ecosystem Considerations

Prey and predators

Pacific Cod are omnivores, eating a diet consisting mainly of marine invertebrates, including amphipods, krill, shrimp and crabs. At around 50-55 cm they also become piscivorous, with Pacific Sand Lance and Pacific Herring becoming important components of their diet. Juvenile Sablefish and adult Pacific Hake have also been reported in the diet of Pacific Cod off the West Coast of Vancouver Island. Pacific Cod have been reported in the diets of Pacific Halibut, Spiny Dogfish, sea birds, seals and sea lions. It has been suggested that availability of Pacific Herring prey could be one driver of Pacific Cod production in Hecate Strait.

Environment

A number of studies have demonstrated linkages between recruitment and environmental indices for Pacific Cod in Hecate Strait. The current dominant hypothesis is an inverse relationship between recruitment and northward water transport of larvae. Northward water transport has been shown to be positively correlated with mean annual sea level at Prince Rupert during the spawning season, which in turn has been used as an explanatory variable for recruitment by a number of studies. Previous stock assessments for Hecate Strait Pacific Cod have incorporated a link to the Prince Rupert sea level in the stock-recruit function (e.g., Sinclair and Starr 2005). These authors found that including sea level information improved the fit to the data but did not greatly influence estimates of biomass in the assessment. The current assessment therefore does not incorporate sea level data. Analyses to be undertaken in 2014 will further investigate linkages between environmental indices and recruitment of Pacific Cod in Hecate Strait.

The Fishery

Pacific Cod in British Columbia are caught almost entirely in the groundfish bottom trawl fishery, which is part of BC's integrated groundfish fishery. Currently, the majority of the BC fishery for Pacific Cod occurs in Hecate Strait (Figure 1). Pacific Cod are distributed throughout Hecate Strait at depths mainly less than 150 m. Pacific Cod density, measured by commercial catch per unit effort, appears to be highest over the Two Peaks/Butterworth, White Rocks, Shell Ground, Reef Island, and Horseshoe fishing grounds (Figure 1). The depth range of capture is approximately 60 – 160 m.

Annual reported catches of Pacific Cod in Hecate Strait have shown considerable variability since the beginning of the time series in 1956 (Figure 2). Bottom trawl fishing effort has been somewhat cyclic in Hecate Strait. In recent years of lower Pacific Cod quotas, many fishing masters have reported active avoidance of Pacific Cod to prevent their quota being exceeded before catching available quotas for other species. Other factors, including changes in markets, introduction of individual quotas, participation in other fisheries, and avoidance of species such as Pacific Halibut, have been identified as influencing effort in the Pacific Cod fishery.

Beginning in 1995, the fishery has been subject to the following management measures: 100% at-sea monitoring, 100% dockside monitoring, individual vessel accountability for all retained and released catch, individual transferable quotas, and reallocation of these quotas between vessels and fisheries to cover catch of non-directed species (see DFO's Pacific Region Groundfish Integrated Fisheries Management Plan). Pacific Cod can be legally discarded by trawlers in BC; however, on-board observers first estimate the quantity being discarded and it is assigned a discard mortality rate which is counted against the vessel's Pacific Cod quota.

In 2012, measures were introduced to reduce and manage the bycatch of corals and sponges by the BC groundfish bottom trawl fishery. These measures were developed jointly by DFO, the fishing industry, and environmental non-governmental organizations. They include: limiting the footprint of groundfish bottom trawl activities, establishing a combined bycatch conservation limit for corals and sponges, and defining encounter protocols. These measures have been incorporated into the Groundfish Integrated Fisheries Management Plan (see link above).

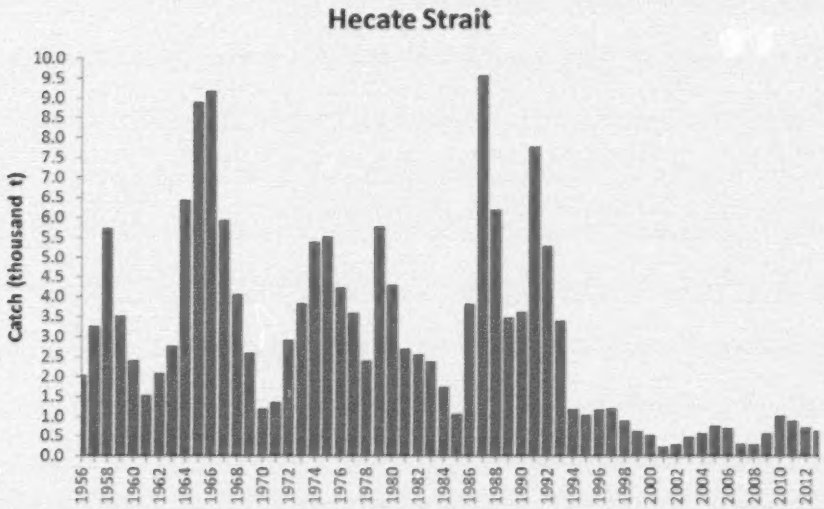

Figure 2. Total catches (thousand tonnes) of Pacific Cod during the period 1956-2012 in Hecate Strait. Catches represent the sum of landings from US and Canadian vessels, and estimated at-sea releases from Canadian vessels. Landings from US vessels ceased after 1978.

STOCK ASSESSMENT

Assessment Methodology

The status of the Pacific Cod population in Hecate Strait was assessed using a Bayesian delay-difference model. The delay-difference model structure tracks the effects of recruitment, survival, and growth on biomass, without requiring a fully age-structured framework, and can perform well, as long as its major assumptions regarding constant growth, knife-edged fishery selectivity and constant natural mortality are met. The model was conditioned on commercial catch data and fit to commercial catch-per-unit-effort (CPUE) data, fishery-independent survey data, and annual estimated mean weights from the commercial fishery.

A Reference Case model and a large set of sensitivity analyses were presented at the review meeting. Model sensitivity was tested to alternative weightings of the index of abundance data, values of fixed variance parameters, and prior probability distributions used for key model parameters, notably natural mortality. Advice to managers is provided using a decision table that summarizes the probability of breaching reference points (Table 2) for a range of fixed catches over a one-year projection. Due to model sensitivity to a number of model assumptions, the decision table uses a model-averaging approach intended to integrate results across alternative model assumptions.

Sources of Data

Catch data were available from 1956 to 2013 (Figure 2) for input into the stock assessment model, including landings data from US and Canadian vessels, and estimates of at-sea releases (discards) from Canadian vessels. Prior to the introduction of 100% at-sea observer coverage in 1996, estimates of at-sea releases were obtained from fishing logbooks and likely underestimate actual releases. Japanese and Soviet vessels also trawled in waters off BC in the late 1960s and early 1970s. These vessels were mainly targeting rockfish and were likely fishing at depths greater than 150 m. Bycatch of Pacific Cod in these fisheries is unknown.

The model was fit to an index of CPUE data derived from key Pacific Cod fishing locations. It is noted that there are a number of problems with the use of commercial CPUE data as an index of biomass for Pacific Cod. It has been suggested that changes in the management regime from an unrestricted fishery prior to 1992, to the introduction of Total Allowable Catches TACs (1992-1996), and then to Individual Vessel Quotas (IVQs) (1997-present), as well as several increases in mesh size, have affected the underlying relationship between commercial CPUE and abundance, and between fishing effort and fishing mortality. The CPUE time series used in the model spanned the period 1956 to 1995, the year before the introduction of 100% observer coverage in the fishery.

Two fishery-independent abundance indices were used: (i) the Hecate Strait multispecies assemblage trawl survey (11 observations between 1984 and 2003); and (ii) the Hecate Strait synoptic groundfish trawl survey (biennial between 2005 and 2013). Annual mean weights from the commercial fishery were estimated using sampled commercial length data and published estimates of growth parameters.

Reference Points

The DFO 'Fishery Decision-making Framework Incorporating the Precautionary Approach' (DFO 2009) requires stock status to be characterized using three reference points: (i) an Upper Stock Reference point (USR); (ii) a Limit Reference Point (LRP); and (iii) a Limit Removal Rate (LRR). Provisional values of USR = 0.8 B_{MSY} and LRP = 0.4 B_{MSY} are suggested in the absence of stock-

specific reference points, where B_{MSY} is the estimated long-term equilibrium biomass when the stock is fished at maximum sustainable yield (MSY).

Large uncertainties in the parameters for natural mortality and steepness of the stock-recruit relationship have resulted in substantial uncertainties in MSY-based reference points for Hecate Strait Pacific Cod in previous assessments (e.g., Sinclair and Starr 2005). In the current assessment, estimates of fishery reference points based on MSY were also very sensitive to model assumptions, and differed substantially among model sensitivity cases. Estimated equilibrium unfished biomass (B_0) was also sensitive to model assumptions. The use of MSY-based or B_0-based reference points were therefore not supported for this stock.

Alternative "historical" reference points are used in the current assessment. These are based on those established in the previous assessment for this stock (Sinclair and Starr 2005), which were accepted by the participants of the 2005 Groundfish Subcommittee Meeting (Fargo 2005). The set of historical reference points consists of:

i. An Upper Stock Reference point (USR) based on the estimated average biomass for the period 1956 to 2004;

ii. A Limit Reference Point (LRP) defined as the estimated minimum biomass from which the stock recovered to an above-average biomass level (namely the estimated biomass in 1971); and

iii. A Limit Removal Rate (LRR) calculated as the estimated average fishing mortality for the period 1956-2004.

Results

Stock trend and Status

Despite large uncertainty, Pacific Cod biomass in Hecate Strait is estimated by the Reference Case model to have been on a gradual, mainly increasing trajectory since 2001 (Figure 3a). The biomass at the beginning of 2014 (B_{2014}) was estimated to be 16,701 t (8,478 t – 33,263 t), where numbers denote median estimates (and 2.5-97.5 percentiles) from the Bayesian posterior results. Estimates of reference points are provided in Table 1. Median recruitment estimates have been below the long-term (56-year) average in most years for the past two decades (Figure 3b).

Model estimates of biomass and current stock status relative to historical biomass were very sensitive to a number of model assumptions. Results were most sensitive to the prior probability distribution for log natural mortality, the influence of the mean weight data, the influence of the commercial CPUE data and the choice to include or exclude the commercial CPUE data. Each of these four issues is addressed in an alternative model configuration (Figure 4).

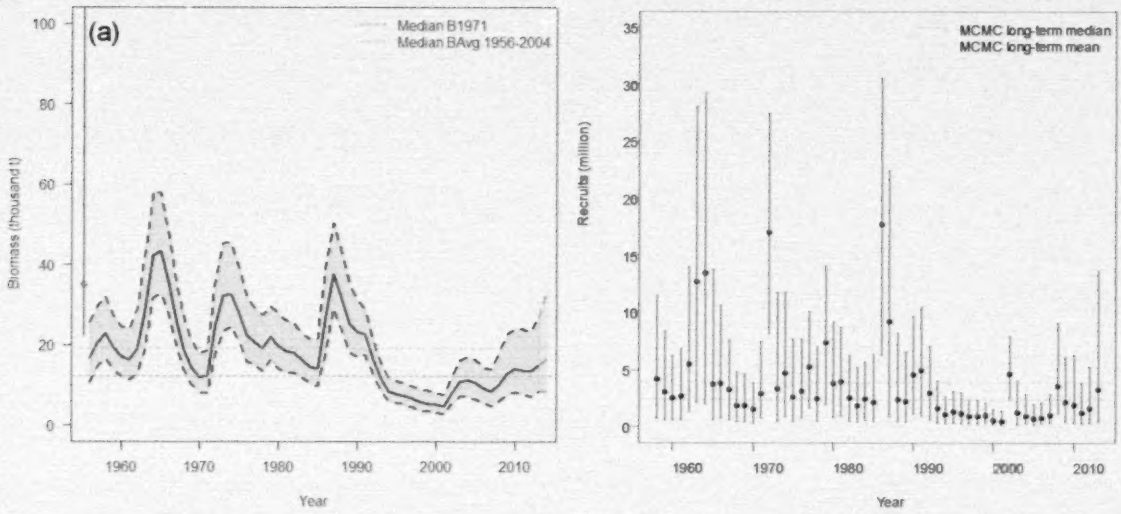

Figure 3. (a) Estimates of biomass (thousand t) for the Reference Case model, shown as medians (solid line) and 95% credibility intervals (2.5 to 97.5 percentiles in grey), with the 2014 projected biomass in red. Estimated equilibrium unfished biomass, B_0, shown as median (open circle) and 95% credibility interval. Horizontal lines are median estimates of the USR (green) and LRP (red). (b) Estimates of age-2 recruits for the Reference Case model with 95% credibility intervals; horizontal lines are long-term (1958-2013) median (red) and long-term mean (green).

Table 1. Estimates of reference points from the Reference Case model as 2.5, 25, 50, 75 and 97.5 percentiles. Medians (50th percentiles) highlighted in bold. F_{2013} is fishing mortality in 2013 and B_{2014} is biomass at the start of 2014. LRP = Lower Reference Point; USR = Upper Stock Reference; LRR = Limit Removal Rate. All biomass units are in thousands of tonnes.

Reference point	2.50%	25%	50%	75%	97.50%
F_{2013}	0.029	0.042	**0.052**	0.065	0.097
B_{2014}	8.478	13.254	**16.701**	21.189	33.263
B_{1971} (LRP)	7.902	10.556	**12.182**	14.143	18.659
$F_{Avg[1956-2004]}$ (LRR)	0.165	0.200	**0.220**	0.239	0.275
$B_{Avg[1956-2004]}$ (USR)	15.685	17.752	**19.258**	21.051	25.567

Harvest Advice

Harvest advice is given in the form of a decision table that summarizes the probability of breaching biomass-based and fishing mortality-based reference points for a range of fixed catch levels that were projected for one year (Table 2). Due to the model's sensitivity to a number of assumptions, the table uses a model-averaging approach intended to integrate uncertainty among the five alternative model configurations shown in Figures 3a and 4 (a through d).

Table 2 shows estimated probabilities of the expected biomass at the beginning of 2015 (B_{2015}) and expected fishing mortality in 2014 (F_{2014}) relative to respective reference points over a range of 2014 projected catch levels. Probabilities are the proportion of the posterior samples from the five model configurations that were below biomass-based reference points, or above fishing mortality-based reference points (e.g., the proportion of posterior samples where B_{2015} < USR or the

proportion of posterior samples where F_{2014} > LRR). Projected log recruitment anomalies in 2015 were drawn randomly from a normal distribution.

Under a 2014 catch similar to the 2013 catch (approximately 700 t), B_{2015} is estimated to have a 0.56 probability of being below the historical USR and a 0.17 probability of being below the historical LRP. The probability that F_{2014} will be above the LRR is estimated to be zero.

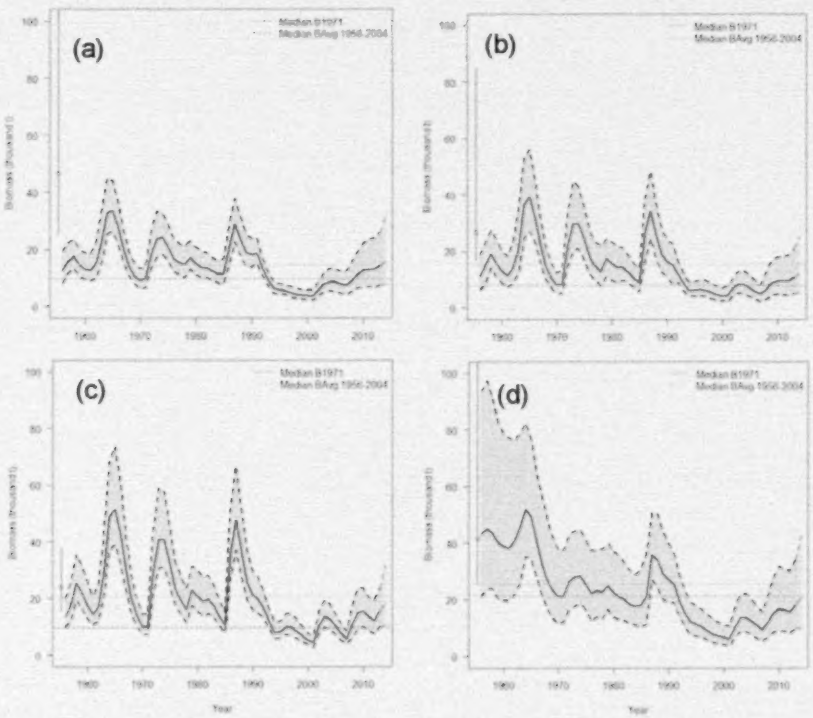

Figure 4. Estimates of biomass and reference points from the four alternative model configurations used with the Reference Case model (Figure 3a) in the model-averaged decision table; see Figure 3a for details of figures. Alternative configurations differed from the Reference Case model in terms of: (a) prior probability distribution for log natural mortality; (b) reduced influence of mean weight data in the objective function; (c) increased influence of commercial CPUE data in the objective function; and (d) exclusion of the commercial CPUE data from the objective function.

Table 2. "Model-averaged" decision table using performance measures based on historical reference points. Each value corresponds to the probability that the performance measure (indicated at the top of the column) will occur under the catch given by the row. B_{2015} is biomass at the start of 2015; F_{2014} is fishing mortality in 2014. Bold rows show current TAC (1200 t) and approximate 2013 catch (~700 t). Figures 3a and show the five model configurations that were averaged to calculate the probabilities.

	Biomass-based measures			Fishing mortality-based measures	
2014 Catch (t)	$P(B_{2015} < B_{2014})$	$P(B_{2015} < \text{LRP})$	$P(B_{2015} < \text{USR})$	$P(F_{2014} > F_{2013})$	$P(F_{2014} > \text{LRR})$
0	0.150	0.146	0.512	0.000	0.000
50	0.159	0.147	0.516	0.000	0.000
100	0.168	0.148	0.520	0.000	0.000
150	0.178	0.150	0.525	0.000	0.000
200	0.187	0.151	0.528	0.000	0.000
250	0.198	0.152	0.532	0.000	0.000
300	0.209	0.155	0.536	0.000	0.000
350	0.220	0.157	0.542	0.000	0.000
400	0.233	0.158	0.545	0.000	0.000
450	0.244	0.161	0.549	0.000	0.000
500	0.254	0.163	0.552	0.004	0.000
550	0.267	0.165	0.554	0.038	0.000
600	0.278	0.166	0.557	0.141	0.000
650	0.289	0.167	0.561	0.3	0.000
700	**0.297**	**0.168**	**0.565**	**0.514**	**0.000**
750	0.310	0.169	0.568	0.682	0.000
800	0.321	0.172	0.572	0.799	0.001
850	0.334	0.173	0.575	0.872	0.002
900	0.346	0.175	0.577	0.917	0.002
950	0.360	0.177	0.580	0.944	0.003
1000	0.372	0.179	0.584	0.961	0.004
1050	0.382	0.182	0.589	0.973	0.006
1100	0.394	0.184	0.593	0.981	0.007
1150	0.409	0.186	0.595	0.985	0.008
1200	**0.421**	**0.188**	**0.598**	**0.989**	**0.009**
1250	0.431	0.190	0.601	0.992	0.013
1300	0.442	0.192	0.603	0.993	0.015
1350	0.453	0.194	0.607	0.994	0.018
1400	0.464	0.196	0.609	0.996	0.021
1450	0.478	0.199	0.612	0.996	0.028
1500	0.490	0.201	0.615	0.996	0.034
1550	0.500	0.203	0.617	0.997	0.040
1600	0.510	0.205	0.621	0.998	0.048
1650	0.521	0.209	0.625	0.998	0.056
1700	0.532	0.212	0.628	0.999	0.068
1750	0.543	0.213	0.631	0.999	0.080
1800	0.553	0.216	0.635	0.999	0.093
1850	0.564	0.218	0.637	0.999	0.109
1900	0.573	0.220	0.640	0.999	0.122
1950	0.585	0.223	0.643	0.999	0.139
2000	0.595	0.226	0.645	1.000	0.153
2050	0.604	0.229	0.647	1.000	0.171
2100	0.615	0.234	0.650	1.000	0.189
2150	0.621	0.236	0.651	1.000	0.209
2200	0.630	0.238	0.654	1.000	0.227
2250	0.637	0.241	0.659	1.000	0.246
2300	0.645	0.244	0.661	1.000	0.266
2350	0.654	0.248	0.665	1.000	0.285
2400	0.643	0.250	0.667	1.000	0.306

Sources of uncertainty

Uncertainty in the estimated parameters and weights assigned to various data components was explicitly addressed using a Bayesian approach and the use of a model-averaged decision table. However, dealing with uncertainty in this way only reflects the set of model configurations included within the assessment. Additional uncertainties in this assessment derive from: (1) the lack of reliable age composition data; (2) relatively short series of fishery-independent abundance indices, which do not have clear trends; and (3) a poor understanding of the relationship between commercial CPUE data and abundance and how it has changed over the course of the fishery. The latter factor, as for many assessments, is a large contributor to the structural uncertainty in this assessment, particularly given the significant changes in management regime, market forces, fishing behaviour, and gear efficiencies that are known to have occurred, as well as being the only source of abundance information before 1984.

A comparison of length-frequency data from the fishery with data from the surveys suggests that the survey selects younger fish than the fishery. Changes to management and fishery practices since the 1950s have almost certainly resulted in changes in fishery selectivity throughout the time series, due to changes in mesh size and potential changes in the spatial distribution of fishing effort (e.g., avoidance of known "hot spots" for Pacific Cod). Therefore, the delay-difference model's assumption of time-invariant, knife-edged selectivity at age two years is very likely to be violated for this stock.

Furthermore, it is unclear whether the Hecate Strait stock is biologically distinct from other surrounding stocks, which obscures the meaning of reference points based on estimates of stock productivity parameters. Other external drivers, including environmental influences (such as northward advection of larvae in years of high sea level) and predator-prey dynamics, have been previously demonstrated to affect Pacific Cod productivity in Hecate Strait, and provide additional uncertainty to understanding stock dynamics and the best approach to management.

Feedback simulation modelling (a component of Management Strategy Evaluation) is recommended to evaluate the performance of alternative management procedures for Pacific Cod under a range of structural uncertainties, including time-varying selectivity, alternative representations of stock structure and alternative drivers of productivity, such as environmental forcing.

CONCLUSIONS AND ADVICE

Despite large uncertainty, biomass of Pacific Cod in Hecate Strait (Area 5CD) is estimated to have been gradually increasing since 2001. Recruitment is estimated to have been below the estimated long-term (56-year) average in most years for the past two decades.

The use of MSY-based and B_0-based reference points could not be supported for this stock. Alternative "historical" reference points are used based on those accepted for the previous assessment of the stock. They are:

i. an Upper Stock Reference point based on the estimated average biomass for the period 1956 to 2004;

ii. a Limit Reference Point defined as the estimated minimum biomass from which the stock recovered to an above-average biomass level (namely the estimated biomass in 1971); and

iii. a Limit Removal Rate calculated as the estimated average fishing mortality for the period 1956-2004.

Advice to managers is provided in a decision table (Table 2) that summarizes the probability of breaching the reference points at a range of fixed catches for a one-year projection. The table uses a model-averaging approach intended to integrate results from the use of alternative model assumptions.

Under a 2014 catch similar to the 2013 catch (approximately 700 t), the projected biomass at the start of 2015 is estimated to have a 0.56 probability of being below the historical Upper Stock Reference point and a 0.17 probability of being below the historical Limit Reference Point. The probability that the fishing mortality rate in 2014 will be above the Limit Removal Rate is estimated to be zero.

SOURCES OF INFORMATION

This Science Advisory Report is from the January 9-10, 2014 Assessment of British Columbia Pacific Cod for Hecate Strait (Area 5CD) and Queen Charlotte Sound (Area 5AB) in 2013. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. (Accessed December 8, 2014)

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ISSN 1919-5087
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Correct Citation for this Publication:

DFO. 2015. Assessment of Pacific Cod (*Gadus Macrocephalus*) for Hecate Strait (Area 5CD) in 2013. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/015.

Aussi disponible en français :

MPO. 2015. Évaluation de la morue du Pacifique (Gadus Macrocephalus) dans le détroit d'Hécate (zone 5CD) en 2013. Secr. can. de consult. sci. du MPO, Avis sci. 2015/015